Final Report

3-D Sound Propagation and Acoustic Inversions in Shallow Water Oceans

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Award Number: N00014-10-1-0040

LONG-TERM GOALS

Underwater sound propagation in the continental shelf is complicated due to many three-dimensional (3-D) oceanographic and marine geologic features, such as shelfbreak fronts, nonlinear internal gravity waves and topographic variability. The long-term goals of this project are targeted on understanding the 3-D sound propagation effects caused by these environmental factors, and also on applying the 3-D sound propagation physics to acoustic inversions.

OBJECTIVES

A verity of physical oceanographic processes and marine geological features can cause horizontal inhomogeneity of the medium properties in the ocean. Thus, horizontal refraction of sound can occur and produce significant 3-D acoustic propagation effects. One of the research objectives of this project is to develop efficient and accurate 3-D models (both theoretical and numerical models) for studying underwater sound propagation in the ocean. Another research objective is to develop acoustic inverse algorithms for source localization and bottom geoacoustic inversions. This work requires a solid understanding on sound propagation physics, and it is closely connected to the first topic.

APPROACH

The technical approaches employed in the 3-D sound propagation study include theoretical analysis, numerical computation and real data analysis. A 3-D normal mode method is used to study canonical environmental models of shelfbreak front systems and nonlinear internal wave ducts. 3-D parabolic-equation (PE) wave propagation models with improved split-step marching algorithms [1-3] are used to study sound propagation in realistic environments. When the acoustic mode coupling can be neglected, a vertical-mode horizontal-PE model is used. Experimental data collected from recent work on the New Jersey shelf (SW06 [4]), the East China Sea (QPE [5]) and the South China Sea (ASIAEX [6] and NLIWI [7]) are analyzed with collaboration with experiment participants.

An adaptive localization method with normal mode theory has been established for localizing low frequency, broad-band signals in a shallow water environment [8]. Gauss-Markov inverse theory is employed to derive an adaptive back-propagation approach. Joining with the maximum a posteriori mode filter, this approach is capable separating signals from noisy data and back-propagating them without significant influence from noise. A two-dimensional (2-D) approach has been developed, and

the theory can be generalized for 3-D cases. This adaptive back-propagation method can also be applied to bottom geoacoustic inversions.

During the Quantifying, Predicting, and Exploiting (QPE [5]) Uncertainty Experiment in 2009, acoustic reflection coefficients and attenuation roll-off rates of the seabed near North Mein-Hua Canyon northeast of Taiwan were measured from chirp sonar echoes. With these measurements, the sediment sound speed, density, medium attenuation are estimated [9] based on the Biot model. The estimated geo-acoustic properties along the chirp sonar track have been further interpolated onto a 2-D horizontal grid using an objective mapping technique. The geo-acoustic parameter maps with error estimates can be used for modeling 3-D underwater sound propagation in the area.

WORK COMPLETED

1. 3-D PE model development

The PE approximation is an effective numerical technique for modeling underwater sound propagation in the ocean. This technique transforms the Helmholtz wave equation into a one-way wave equation that can be solved by a variety of marching algorithms. Among those algorithms, the split-step Fourier (SSF) method is most efficient for 3-D cases, because we can employ the Fast Fourier Transform to calculate the second-order spatial derivatives. We have implemented the split-step Fourier method in both Cartesian and cylindrical coordinate systems [1] with a grid size requirement derived from the sampling theory:

$$\text{DFT sampling theory} \quad \begin{cases} k_{y\ max} = \pi/\Delta y\,, \Delta k_y = \pi/L_y & (|y| \le L_y, |k_y| \le k_{y\ max}) \\ k_{z\ max} = \pi/\Delta z\,, \Delta k_z = \pi/L_z & (|z| \le L_z, |k_z| \le k_{z\ max}) \\ k_{\theta\ max} = \pi/\Delta \theta\,, \Delta k_\theta = \pi/L_\theta & (|\theta| \le L_\theta, |k_\theta| \le k_{\theta\ max}) \end{cases},$$

where $k_{y,z,\theta}$ are the wavenumbers along the transverse, vertical and angular axes. This relations are fundamental, and they actually govern the requirements for the model grid size. Consieder that the goal of sound propagation modeling is to resolve all of the arrivls less than a given arrival angle $|\zeta| \le \zeta_{max}$ with a requried angular resolution $\Delta\zeta_{min}$. From ζ_{max} we can find that the maximal wave-numbers need to be $k_{y,z\ max} \ge k_0 \sin\zeta_{max}$ and $k_{\theta\ max} \ge k_0 r \sin\zeta_{max}$, or equivalently for Δy, Δz, and $\Delta\theta$:

$$\boxed{\Delta y, \Delta z \le \left(\sin\zeta_{max}\right)^{-1} \lambda_0/2 \ \text{ and } \ \Delta\theta \le \left(r\ \sin\zeta_{max}\right)^{-1} \lambda_0/2\,.}$$

From the requiement of angular resolution $\Delta\zeta_{min}$, we can also find that the wavenumber increment $\Delta k_{y,z} \le k_0 \cos\zeta\, \Delta\zeta_{min}$ and $\Delta k_\theta \le k_0\,(r\cos\zeta\, \Delta\zeta_{min} + \sin\zeta\, \Delta r)$, or equivalently for the apertures L_y, L_z and L_θ,

$$\boxed{L_{y,z} \ge (\cos\zeta\, \Delta\zeta_{min})^{-1} \lambda_0/2 \ \text{ and } \ L_\theta \ge (r\cos\zeta\, \Delta\zeta_{min} + \sin\zeta\, \Delta r)^{-1} \lambda_0/2\,.}$$

From this analysis, one can see that in cylindrical PE the model resoultion degrades as the range goes further. To overcome the problem, two improved model grids are suggested, as shown in Figure 1. The performance of different PE models is shown in Figure 2, and one can see that the

Cartesian PE and the cylindrical PE with adaptive grids agree with each other very well. On the other hand, the coarse-grid cylindrical PE produces large errors due to the degration of model resolution.

To increase the accuracy of SSF PE models, we developed the following operator splitting algorithm for the square-root Helmholtz operator to include higher-order cross terms [2].

$$\begin{aligned}\sqrt{1+\mathcal{A}+\mathcal{B}} \cong & \sqrt{1+\mathcal{A}}+\left(-1+\sqrt{1+\mathcal{B}}\right)-\frac{1}{2}\left(-1+\sqrt{1+\mathcal{A}}\right)\left(-1+\sqrt{1+\mathcal{B}}\right) \\ & -\frac{1}{2}\left(-1+\sqrt{1+\mathcal{B}}\right)\left(-1+\sqrt{1+\mathcal{A}}\right),\end{aligned} \tag{1}$$

Because the resultant models can handle larger propagation angles and greater refractive index anomalies, the long-standing issue for the SSF method on handling the interface condition at the seafloor have been solved. An example of 3-D sound propagation modeling with the higher order split-step Fourier PE method is shown in Figure 3. We have also applied this new higher order operator splitting to other PE models using the Alternative Direction Implicit (ADI) method, which divide the two-dimensional (2-D) derivative operator into two one-dimensional (1D) operators for vertical and horizontal derivatives. It has been shown that 3-D PE models using the alternative direction method but neglecting cross terms of the two 1D derivative operators will not have the original wide-angle capability. Since our higher order operator splitting method considers the cross terms, the resultant models have better accuracy [3].

2. Whispering gallery modes in nonlinear internal wave ducts

Using 3-D normal mode theory, general solutions of sound pressure field in a curved internal wave duct is found:

$$\mathrm{p}(r,\theta,z) =$$

$$\sum_{m,n} \mathrm{C}_{mn} \underbrace{\left[\mathrm{A_d}\, e^{i(k^2(z)-\zeta_m^2)^{\frac{1}{2}}z} + \mathrm{A_u}\, e^{-i(k^2(z)-\zeta_m^2)^{\frac{1}{2}}z}\right]}_{\text{vertical modes}} \times \underbrace{\left[\mathrm{B_{out}}\, H^{(1)}_{\eta_{mn}}(\zeta_m r) + \mathrm{B_{in}}\, H^{(2)}_{\eta_{mn}}(\zeta_m r)\right]}_{\text{radial modes}} \times e^{i\eta_{mn}\theta}$$

where

$$H_v^{(1)}(x) = J_v(x) + i\, Y_v(x)$$

$$H_v^{(2)}(x) = J_v(x) - i\, Y_v(x)$$

The field is decomposed into vertical and radial components. For each vertical mode, there is a set of radial modes, which is a form of Bessel functions descrbing the horizontal component of the field. Also, the radial modes can propagate along the wave front. Two types of modes are found. One is the whispering gallery modes formed by the sound energy trapped by the outter wave. The other is full bouncing mode generated by the sound energy bouncing between inner and outter waves.

This whispering gallery type of acoustic ducting effect in a curved nonlinear wave duct is studied through idealized models [10]. The internal wave ducts are 3-D, bounded vertically by the sea surface and bottom, and horizontally by aligned wavefronts. Both normal mode and PE methods are taken to analyze the ducted sound field. The ducting condition depends on both internal-wave and acoustic-source parameters, and a parametric study is conducted to derive a general pattern. The PE

method provides full-field modeling of the sound field, so it includes other acoustic effects caused by internal waves.

An exmple of 75 Hz sound propagation in a curved nonlinear internal wave duct with 25 km curvature is shown in Figrue 4. The upper panels show the vertical modal structure, and the lower panels are the full field solution from the WHOI 3-D PE method. The radial mode shapes indicate that the lower order radial modes are whiserping gallery modes, since they are formed by the sound energy trapped by the outter wave.

3. Estimating Geo-acoustic properties using a chirp sonar sub-bottom profiler

The PI has worked with colleagues from Taiwan (Prof. Linus Y.S. Chiu of National Sun Yat-Sen University and Dr. Andrea Chang of National Taiwan University) on estimating the compressional wave speed, density, and medium attenuation of the surficial sediments near North Mein-Hua Canyon northeast of Taiwan based on the chirp sonar echoes collected during the Quantifying, Predicting, and Exploiting (QPE) Uncertainty experiment funded jointly by the ONR and the National Science Council of Taiwan. The estimation was based on the Biot model [11] and followed Schock's inversion procedure [12-13]. After the sediment geo-acoustic properties along the chirp sonar track were estimated, 2-D spatial distributions were generated using an objective mapping method. The surveyed region and the 2-D sediment property maps are shown in Figure 5.

4. 3-D sound propagation effects caused by topographic variability

Two types of topographic features that will cause 3-D sound propagation effects have been studied. The first feature is the seafloor scours. Because the bottom scours often have strong directivity, propagating sound will be focused along the scouring direction due to the transverse gradient on the bottom depth. Also, the horizontal focusing will vary with the source position. Using the method of vertical model and horizontal PE, a 3-D sound propagation model with the adiabatic mode assumption is built. This model has been applied for an SW06 example. The model clearly shows that due to the seafloor scours in the New Jersey shelf area propagating sound can be focused, as shown in the upper panel of Figure 6. Two source positions are modeled in the example, and the resultant focusing patterns are slightly different. Although the effects of the seafloor scours are profound, they will be masked episodically by the presence of water column fluctuations, such as nonlinear internal waves. Twenty-two-days data are used, and a long time average is taken for removing the episodic fluctuations. The data shows about 5-dB intensification due to the horizontal focusing. The data-model comparison is shown in the lower panel of Figure 6, and has very good agreement.

The second bathymetric feature that will cause strong 3-D sound focusing is the submarine canyon. A realistic model has been implemented to model 3-D sound propagation in the North Mien-Hua canyon northeast of Taiwan, see Figure 7. Because of the concave bathymetry, the sound reflected the seafloor will be focused, as shown in the lower panel of Figure 7. This also provides a plaussible explanation for the intensified ship noise recorded at a hydrophone array during the QPE experiment. This 3-D sound focusing effect caused by submarine canyons has also been studied using transmission loss (TL) data collected during the QPE experiment, where a mobile acoustic source was utilized to study sound propagation over North Mein-Hua Canyon. The WHOI 3-D PE models [1-3] are employed to explain the underlying physics. The acoustic data show a significant decrease in sound intensity as the source crossed over the canyon, and the numerical models provide a physical insight

into this shadowing effect (see Figure 8). In addition, the model suggests that 3-D sound focusing due to the canyon seafloor can occur when the underwater sound propagates along the canyon axis.

5. Adapative normal mode back-propagation approach

A variety of localization methods with normal mode theory have been established for localizing low frequency, broadband signals in a shallow water environment. Gauss-Markov inverse theory is employed in this paper to derive an adaptive back-propagation approach. Joining with the *maximum a posteriori* mode filter, this approach is capable separating signals from noisy data and back-propagating them without significant influence from noise. Numerical simulations are presented to demonstrate the robustness and accuracy of the approach presented, along with comparisons to other methods. Applications to real data collected from the SW06 experiment are presented in Figure 9, and the effects of water column fluctuations with scales from nonlinear internal waves to shelfbreak front variability are observed.

RESULTS

The major results of this project are summaried here, along with a publication list provided later. First, it is found that 3-D Cartesian PE models can retain uniform resolution as the solution marches forward, but their PE approximation errors vary in azimuth. On the other hand, cylindrical models have consistant PE approximation in each azimuth, but they cannot maintain uniform resolution [1]. Improvement has been made for 3-D Cartesian split-step Fourier PE to handle greater propgation angles [2], and a comparsion of the PE solution to an analytical solution for a wedge problem is shown in Figure 1. Two new cylindrical model grids have also be introduced to improve the resolution of 3-D cylindrical PE models [1]. Also, an improved operator splitting algorithm is applied to the split-step Padé type PE mothod [3].

Theoretical and numerical investigations of 3-D sound propagation have been carried out to study effects due to nonlinear internal waves (NIW), idealized shelfbreak fronts and topography. Major findings are summarized here. Acoustic ducitng by curved NIW has strong acoustic modal dependency, and higher order modes tend to have better ducting conditions [6]. An example of acoustic ducting by a pair of curved NIWs is shown in Figure 4. A realistic sound propagation model has successfully reproduced the sound focusing effect by NIWs, and a horizontal Lloyd's mirror effect from NIW fronts was observed in SW06 experimental data. Evidents of horizontal focusing due to seafloor scours and submarine canyons were also found. The experimental and numerical studies show that the sound intesnity variability due to these 3-D effects are sigificant (4 to 15 dB).

An adaptive normal mode back propa-gation approach employing Gauss-Markov inverse theory has been developed for low-frequency broadband sound source localization. This method can adapt to the signal-to-noise ratio and ensure an optimal balance between robustness and accuracy. Lastly, an objective mapping method have been empolyed to interpolate the geo-acoustic properties inverted from chirp sonar echoes during the QPE experiment. This geo-acoustic information can significantly improve underwater sound propagation models

IMPACT/APPLICATIONS

The potential relevance of this work to the Navy is on increasing the capability of sonar systems in shallow water areas. The contributions of the effort on studying 3-D sound propagation

effects will be on assessing the environment-induced acoustic impacts. In addition, the investigation of acoustic inversions directly relates to the Navy sonar operation.

RELATED PROJECTS

Experimental data were collected from the ONR ASIAEX, SW06 and QPE projects. Also, collabration with Drs. T.F. Duda, J.M. Collis and Mr. A.E. Newhall on developing 3-D PE models is through an ONR MURI project, Integrated Ocean Dynamics and Acoustics (IODA).

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PUBLICATIONS

1. Peer refereed papers

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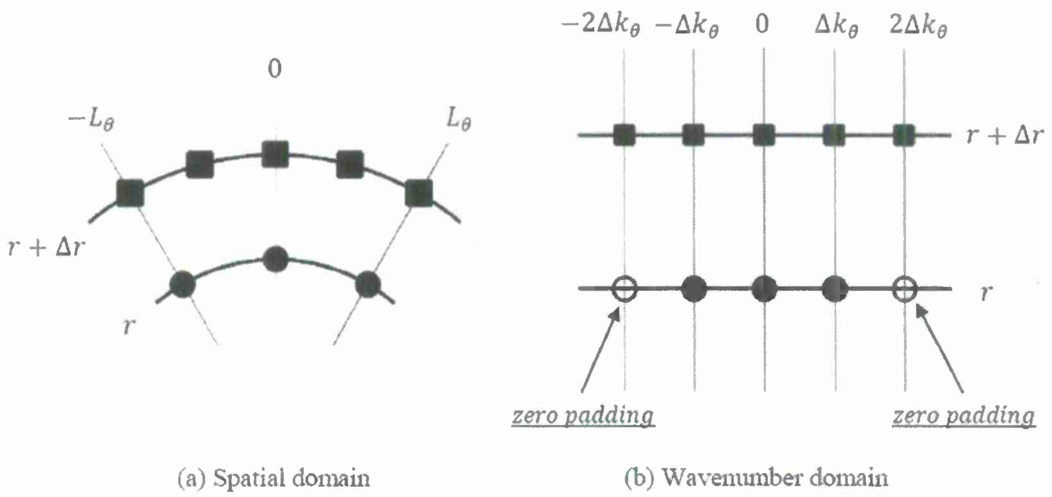
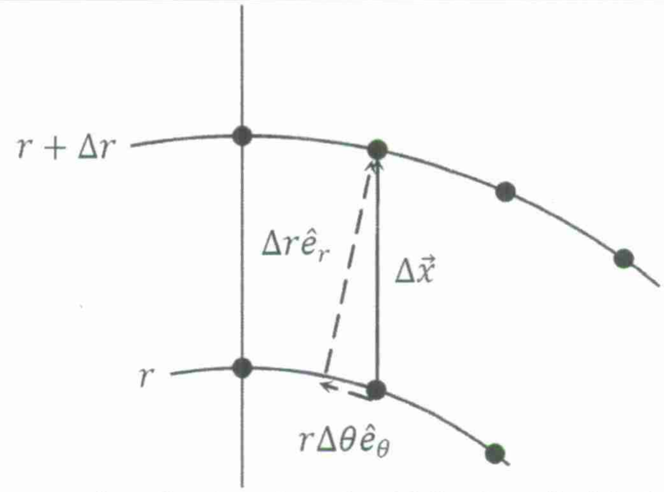


Upper panels: Upsampling of angular grid points in the cylindrical PE model



Lower panel: A fixed arc-length grid for the cylindrical PE model

Figure 1. Two improved model grids for the cylindrical PE model
[Upper panels show the zero-padding on the wavenumber spectrum results in upsampling of angular grids. Lower panel shows the free propagation path occurred in a fixed arc-length grid.]

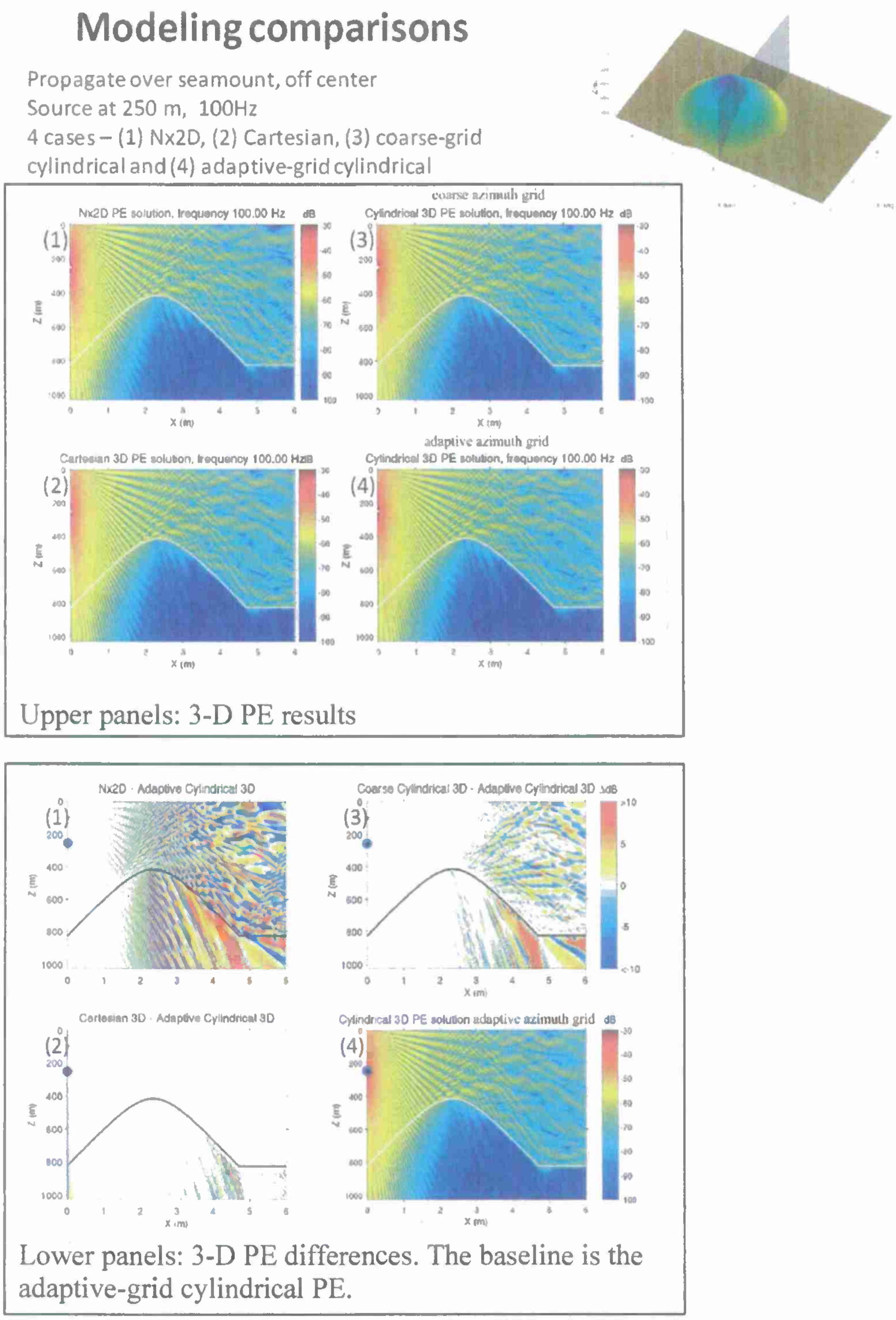


Figure 2. PE model comparisons

[Sound propagation over a seamount are computed by different 3-D PE models, including (1) Nx2-D (2) Cartesian, (3) coarse cylindrical grid and (4) adaptive cylindrical grid. The computed sound fields are shown in the upper panels, and the model differences are shown in the lower panels. The Cartesian PE and the cylindrical PE with an adaptive grid have very good agreement.]

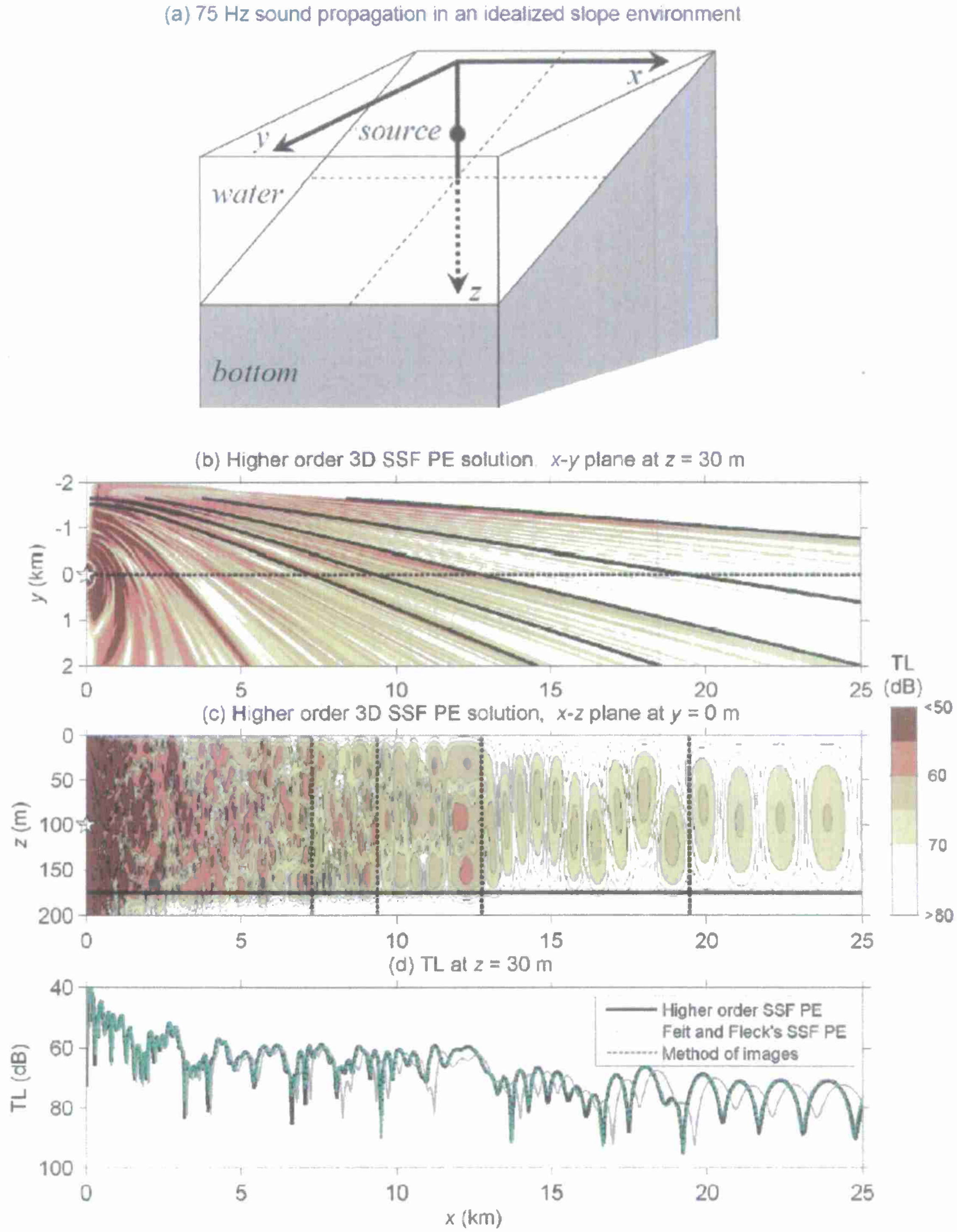


Figure 3. An example of 3-D sound propagation modeling with the higher order split-step Fourier PE method shown in Ref. 2.
[(a) Geometry of the idealized wedge example. (b) Transmission loss (TL) contours on the horizontal x-y plane at depth 30 m. (c) TL contours on the vertical x-z plane along y = 0. The solid lines in (b) are the hyperbolic loci of the first five modal caustics predicted by a modal theory, and the dashed lines in (c) denote the theoretical cutoff locations of modes 2-5. (d) shows an excellent agreement between the higher order PE and an analytical solution derived from a method of images.]

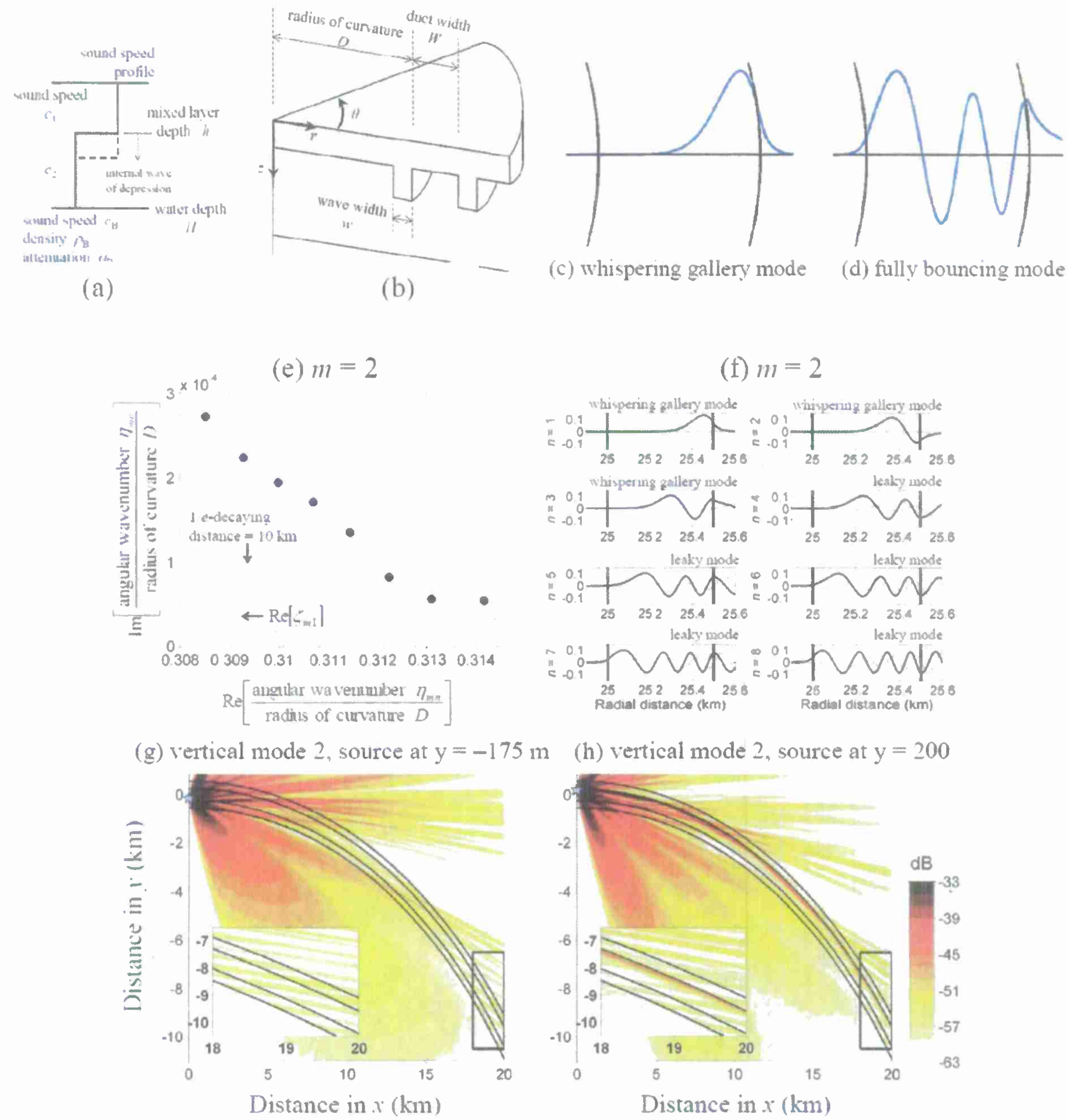


Figure 4. Analytical study of acoustic ducting by a pair of curved internal waves.
[(a) A two-layer water column perturbed by internal waves of depression. (b) The shaded area indicates the upper layer with sound speed c_1 higher than the sound speed c_2 in the lower water column. (c) and (d) Two types of radial modes can be found in a curved internal wave duct. (e)-(f) Horizontal ducting of vertical mode 2 at 75 Hz in a curved internal wave duct. The radius of internal wave curvature is 25 km. The ratios of the radial modoal eigenvalues to the radius of internal wave curvature are shown in (e), and the radial mode functions are shown in (f). The horizontal ducting of vertical mode 2 is calculated with the WHOI 3-D PE method. Two different source locations are considered: (g) near the inner wave and (h) near the outer wave. Modal intensity is shown, and the edges of internal waves are indicated by the solid curves. The inset figure in (g) and (h) is a closer view of the area marked by the box. Whispering gallery-type ducting is seen in this case when the source is close to the outer wave.]

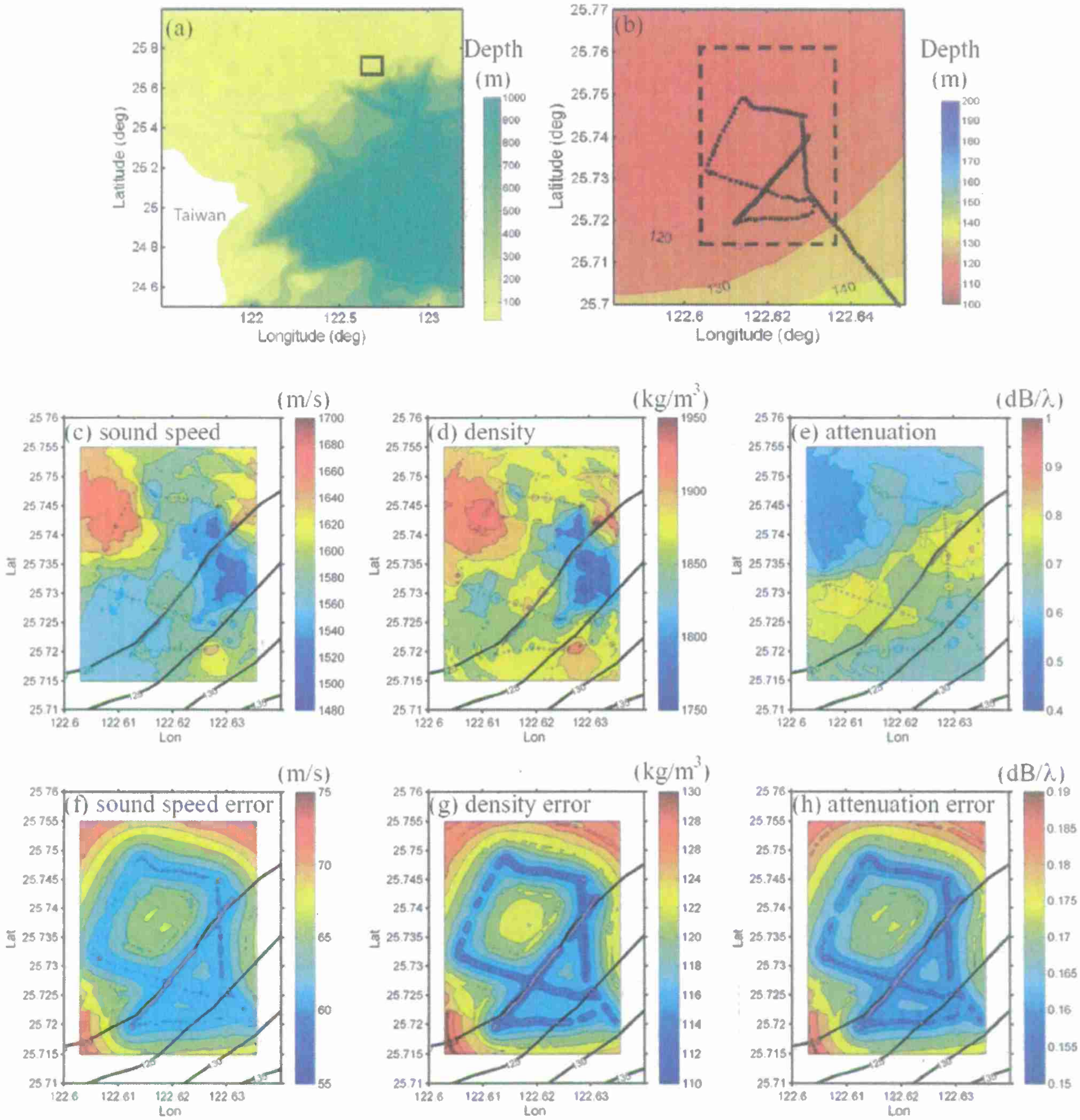
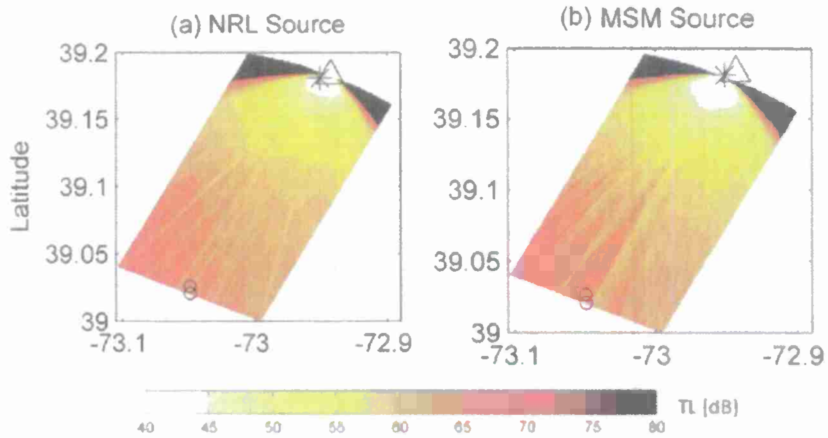
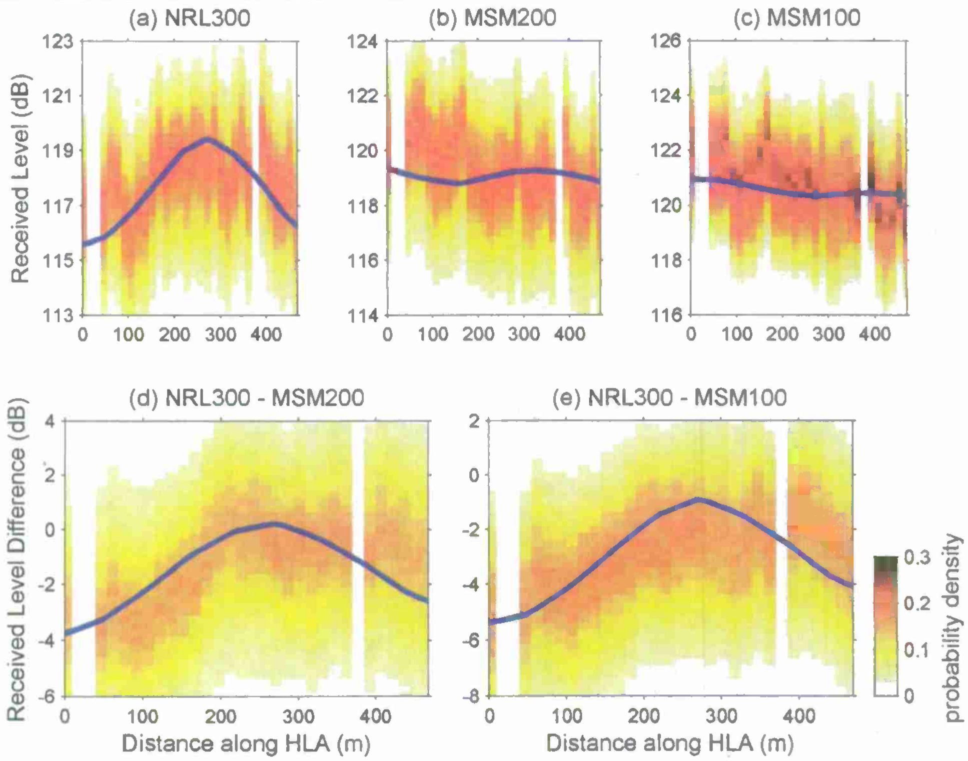


Figure 5. Estimation of the surficial sediment geo-acoustic properties using a chirp sonar sub-bottom profiler northeast of Taiwan.
[(a) Location of the study area. (b) Chirp sonar survey track. (c)-(e) Objectively interpolated 2-D maps of sediment sound speed, density and attenuation using inverted property values along the sonar track.(f)-(h) 2-D maps of the expected interpolation errors.]

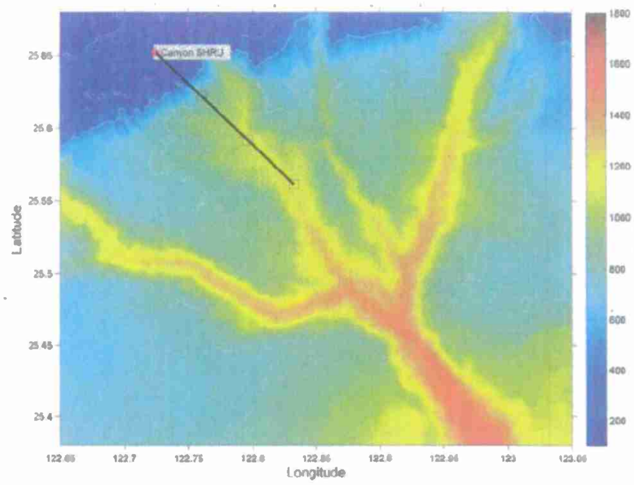


Upper panels: the horizontal refraction of propagating sound from two different moored sources in the SW06 experiment. (Model results)

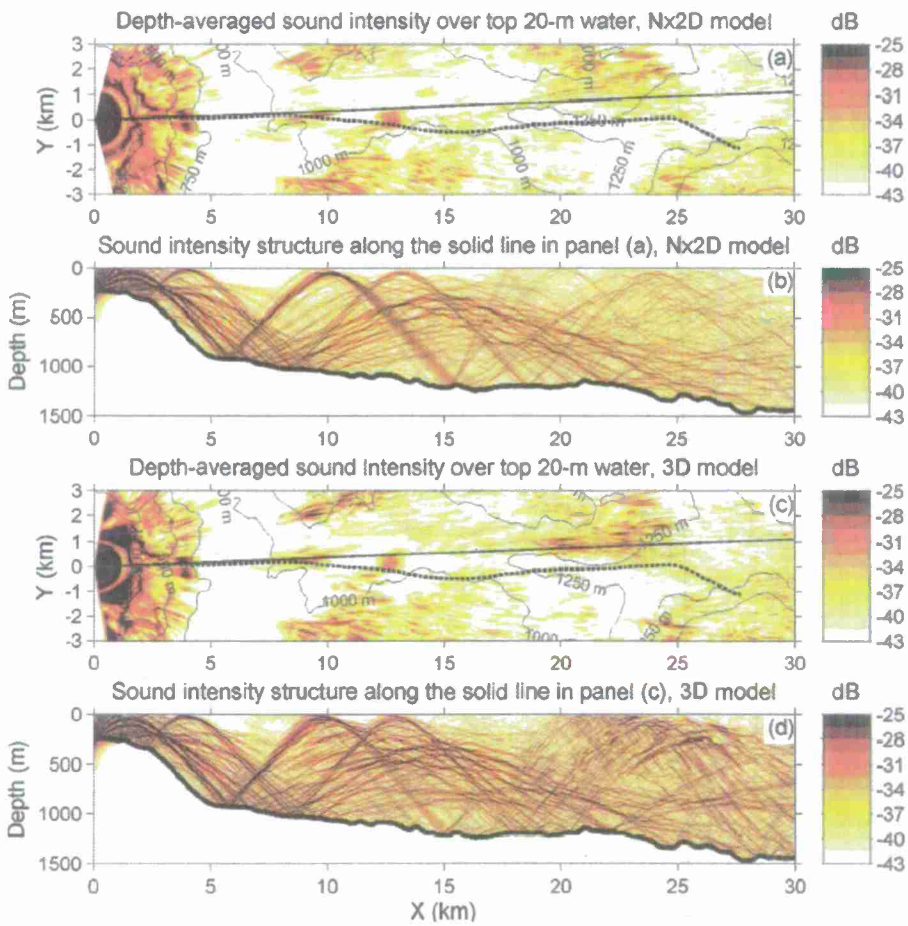


Lower panels: Data-model comparison of the horizontal refraction caused by the seafloor scours in the SW06 experiment. The data is shown as probability density, and the model is shown in blue curves and presenting the mean field.

Figure 6. Horizontal refraction of sound caused by seafloor scours
[Acoustic data and models demonstrate the acoustic effect of seafloor scours on horizontal refraction. The model well captures the energy focus seen in the data. The sound frequencies are 100, 200 and 300 Hz.]



(a) Bathymetry of the North Mien-Hua Canyon, northeast of Taiwan



(b) Comparison of Nx2-D and 3-D PE models. Acoustic frequency 300 Hz.

Figure 7. Modeling of sound propagation over a submarine canyon
[The bathymetry of the canyon system is shown in the panel (a), and the PE models are shown in panel (b). From the differences between the Nx2-D and 3-D PE's, one can see that the canyon bathymetry causes very strong sound focusing. The cylindrical spreading loss is removed in the plots to reduce the dynamic range of the TL variability.]

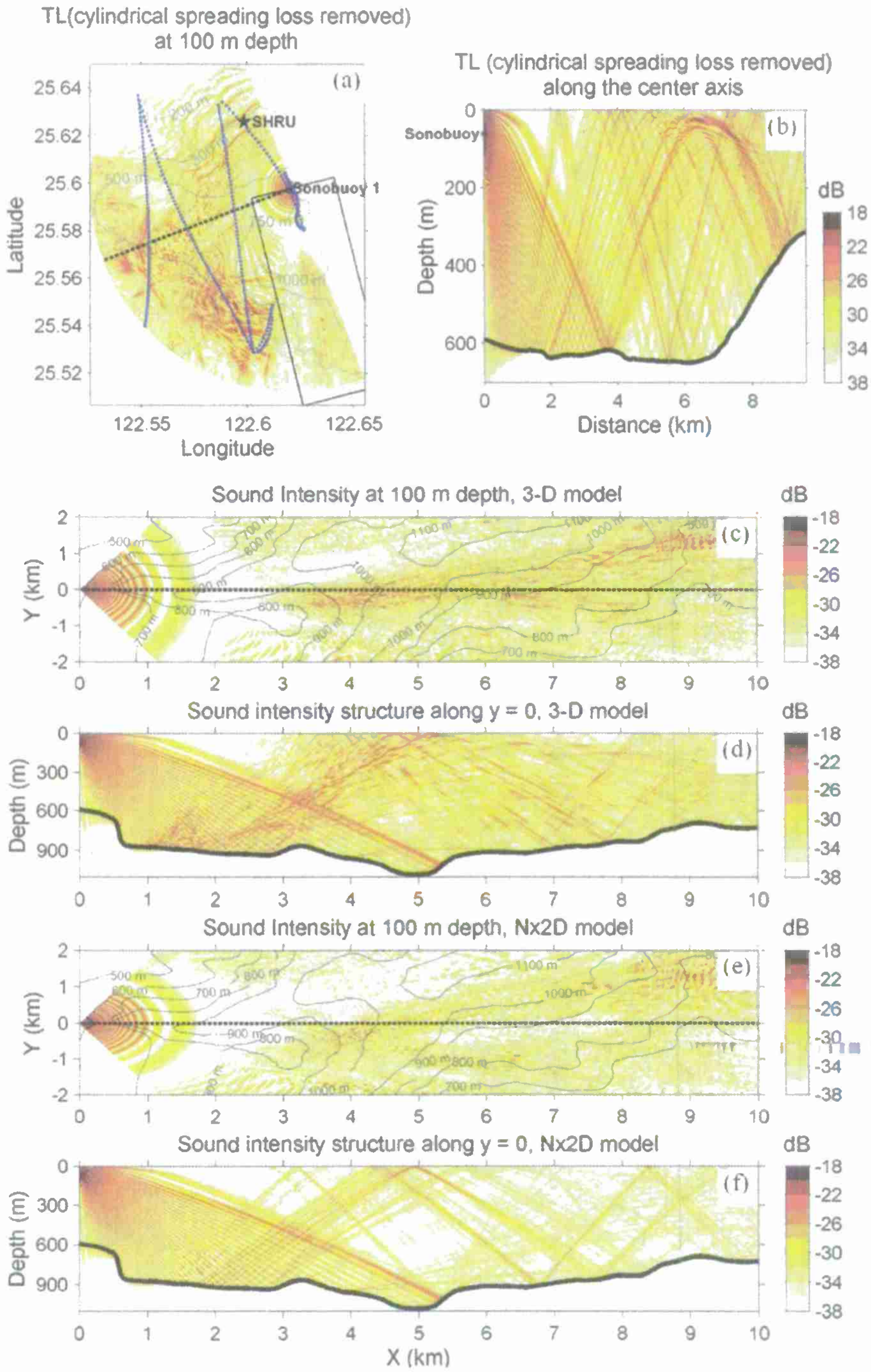
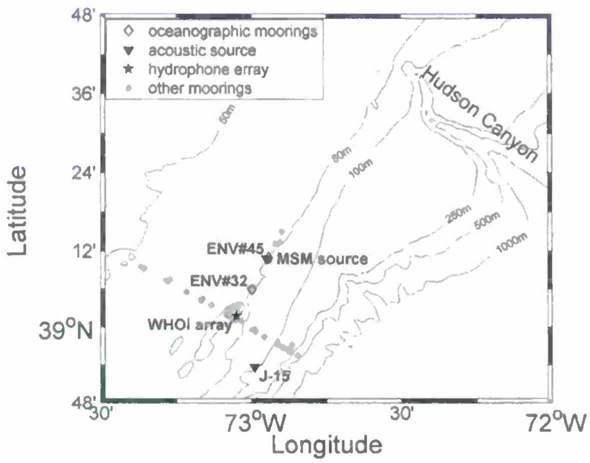
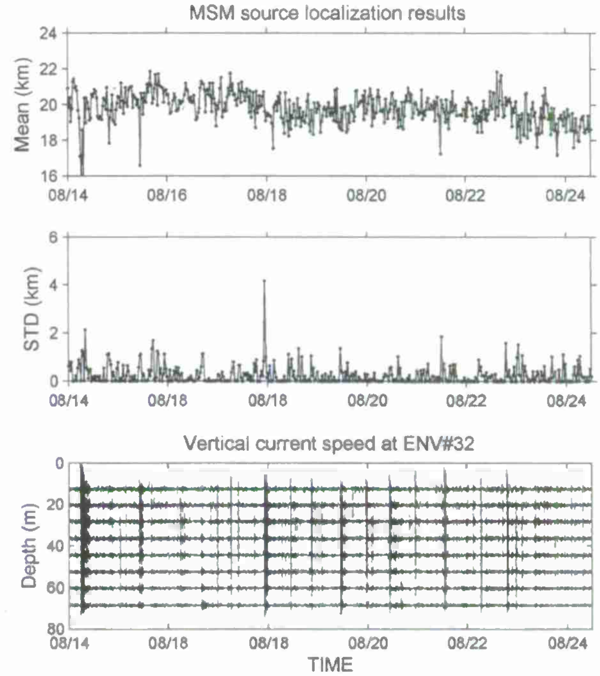


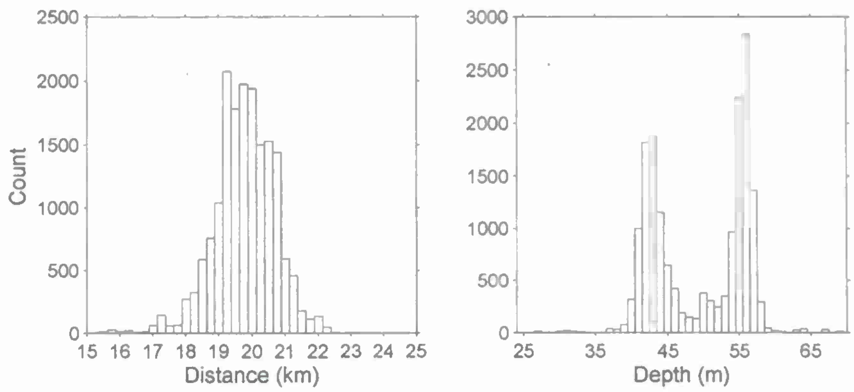
Figure 8. Transmission loss models for sound emitted from a mobile acoustic source deployed during the QPE experiment over North Mein-Hua Canyon.
[The source track is denoted by the dotted line in panel (a). Two types of acoustic signal receiving units were deployed (sonobuoys and WHOI SHRU arrays). The WHOI cylindrical 3-D PE model [1] was used to simulate underwater sound propagation over the canyon area. The color images show the TL predictions. The model suggests that when sound propagates along the canyon axis, as noted by the box in panel (a), a 3-D focusing effect can occur due to sound reflection from the concave canyon seafloor. This focusing effect can be confirmed from examining the difference in 3-D and N×2-D models, as shown in panels (c) to (f).]



(a) SW06 experimental area and mooring locations



(b) Effects of nonlinear internal waves on MSM source localization.



(c) Distributions of MSM source localization results from the normal-mode back-propagation approach. The true source location was at 19.75 km in distance and 55 m in depth.

Figure 9. Source localization using the adaptive normal-mode back-propagation method [The adaptive normal-mode back-propagation method is applied to the SW06 data. Processed signals are from one of the moored sources in the experiments, the MSM source shown in the panel (a), and the source localization results are shown in the panel (b) to correlate with the nonlinear internal wave signals measured at the environmental mooring ENV#32. A positive correlation can be seen. Distributions of the source localization results are shown in the panel (c), showing very good source range estimation. The bimodal distribution of the source depth estimates is most likely caused by unresolved mode coupling effects.]

REPORT DOCUMENTATION PAGE			*Form Approved* *OMB No. 0704-0188*
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1. REPORT DATE *(DD-MM-YYYY)* 12/19/2012	**2. REPORT TYPE** FINAL		**3. DATES COVERED** *(From - To)* 12/01/2009 - 09/30/2012
4. TITLE AND SUBTITLE 3-D Sound Propagation and Acoustic Inversions in Shallow Water Oceans			**5a. CONTRACT NUMBER** N/A
			5b. GRANT NUMBER N00014-10-1-0040
			5c. PROGRAM ELEMENT NUMBER N/A
6. AUTHOR(S) Ying-Tsong Lin			**5d. PROJECT NUMBER** 140040SP
			5e. TASK NUMBER N/A
			5f. WORK UNIT NUMBER N/A
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Woods Hole Oceanographic Institution 98 Water Street, MS #11 Woods Hole, MA 02543			**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Office of Naval Research, Code 32 One Liberty Center 875 N. Randolph Street, Suite 1425 Arlington, VA 22203-1995			**10. SPONSOR/MONITOR'S ACRONYM(S)**
			11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution is unlimited			
13. SUPPLEMENTARY NOTES None			
14. ABSTRACT See Attached			
15. SUBJECT TERMS Ocean Acoustics; Oceanography;3-D Sound Propagation			

20121226001

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Dr. Ying-Tsong Lin
					19b. TELEPHONE NUMBER *(Include area code)*
U	U	U	U	18	508-289-2329